The influence of AlGaN/GaN superlattices as electron blocking layers on the performance of blue InGaN light-emitting diodes*

Gong Chang-Chun(龚长春), Fan Guang-Han(范广涵)†, Zhang Yun-Yan(张运炎), Xu Yi-Qin(许毅钦), Liu Xiao-Ping(刘小平), Zheng Shu-Wen(郑树文), Yao Guang-Rui(姚光锐), and Zhou De-Tao(周德涛)

Institute of Opto-Electronic Materials and Technology, South China Normal University, Guangzhou 510631, *China*

(Received 24 June 2011; revised manuscript received 14 November 2011)

P-AlGaN/P-GaN superlattices are investigated in blue InGaN light-emitting diodes as electron blocking layers. The simulation results show that efficiency droop is markedly improved due to two reasons: (i) enhanced hole concentration and hole carrier transport efficiency in AlGaN/GaN superlattices, and (ii) enhanced blocking of electron overflow between multiple quantum-wells and AlGaN/GaN superlattices.

Keywords: P-AlGaN/P-GaN superlattices, numerical simulation, efficiency droop

PACS: 85.60.Jb，85.50.–n，87.15.A–, 78.60.Fi **DOI:** 10.1088/1674-1056/21/6/068505

1. Introduction

Blue InGaN light-emitting diodes (LEDs) have been extensively developed for several important applications, e.g. full-color displays, LCD back-lighting, mobile platforms, and illumination.[1−3] However, InGaN LEDs suffer from the problem of efficiency droop at high current. The internal quantum efficiency (IQE), defined as the ratio of the number of photons generated in the active region to the number of carriers injected into the LED device, usually decreases with a further increase in current.[4,5] The radiative recombination rate and the output power of the InGaN LED are thus degraded correspondingly.[6,7] It is imperative to improve the IQE so that LEDs can produce high luminous flux with reasonably high efficiency at high current densities. Recently, different explanations for efficiency droop have been proposed, including leakage current resulting from the piezoelectric effect,[7] carrier injection efficiency,[8] Auger recombination,[9] and junction heating.[10]

As is well known, the hole in GaN-based material has a relatively high effective mass and therefore a very low mobility. It is difficult for holes to be injected into and transported in the active region. Thus, a large number of holes accumulate in the last quantum well (QW) next to the p-type region. As for the electrons, due to their opposite characters to those of holes and the insufficient blocking efficiency of the traditional P-AlGaN electron-blocking layer (EBL), they can transport easily in the active region and even overflow across the EBL to the p-type region. As a result, nonuniform distribution of carriers is formed, which explains why not every QW contributes to radiative recombination. For blue InGaN LEDs, the poor hole injection efficiency that leads to serious electron leakage may be closely related to the reduction in IQE at high current. Some theoretical investigations have been performed previously on the band structures of superlattices,[11,12] and additionally, a different approach using an inserted superlattice structure to obtain better optical characteristics has been reported experimentally.[13−16] Recently, it has been numerically studied that AlGaN/GaN/InGaN superlattices were incorporated into an InGaN-based blue LED as an electron blocking layer to minimize the temperature dependence on optical output power.[17] In this paper, we propose to replace the traditional p-AlGaN layer with P-AlGaN/P-GaN superlattices (AlGaN/GaN SLs) as the EBL. The physical and the optical properties of the blue InGaN LEDs with P-AlGaN and AlGaN/GaN SLs are studied with the ad-

*Project supported by the Project of Combination of Production and Research Guided by Education Ministry of China in 2009 (Grant No. 2009B090300338) and the LED Industrial Projects of Special Funds Strategic Emerging Industries in 2011, Guangdong Province, China (Grant No. 2010A081002005).

†Corresponding author. E-mail: gfan@scnu.edu.cn

© 2012 Chinese Physical Society and IOP Publishing Ltd

vanced physical model of semiconductor device (APSYS) simulation program, which is capable of dealing with the physical properties of LEDs by solving Poisson's equation, the current continuity equation, the carrier transport equation, the quantum mechanical wave equation, and the photon rate equation.

2. Structure and parameters

The original blue InGaN LED used as a reference was grown on a *c*-plane sapphire substrate, then a 0.5-μm thick undoped-GaN layer and a 4.5-μm thick n-GaN layer (n-doping= 5×10^{18} cm^{-3}) were deposited on it. The InGaN/GaN multiple quantum-well (MQW) structure consisted of five 2 nm-thick $In_{0.13}Ga_{0.87}N$ well layers and six 15 nm-thick GaN barrier layers. A 20-nm thick P-$Al_{0.2}Ga_{0.8}N$ (p-doping= 3×10^{17} cm^{-3}) electron-blocking layer (EBL) was grown on the top of the MQW. Finally, a 0.2-μm thick P-GaN (p-doping= 7×10^{17} cm^{-3}) cap layer was grown. The device geometry was designed into a rectangular shape of 300 μm × 300 μm. For the LED with AlGaN/GaN SLs, the P-AlGaN EBL was replaced by an AlGaN/GaN SL EBL, which is composed of a 10-period AlGaN/GaN (2 nm/2 nm, p-doping= 3×10^{17} cm^{-3}) SLs.

The bandgap energies of the InGaN, AlInN, and AlGaN ternary alloys can be expressed as[18]

$$E_g(In_xGa_{1-x}N) = x \cdot E_g(InN) + (1-x) \cdot E_g(GaN) - 1.4x \cdot (1-x), \quad (1)$$

$$E_g(Al_xIn_{1-x}N) = x \cdot E_g(AlN) + (1-x) \cdot E_g(InN) - 3.4x \cdot (1-x), \quad (2)$$

$$E_g(Al_xGa_{1-x}N) = x \cdot E_g(AlN) + (1-x) \cdot E_g(GaN) - 0.7x \cdot (1-x), \quad (3)$$

where E_g(InN), E_g(AlN), and E_g(GaN) are the bandgap energies of InN, AlN, and GaN, with values of 0.78, 6.25, and 3.51 eV, respectively.[18] The operating temperature is assumed to be 300 K, and the light extraction efficiency is assumed to be 0.78. Other material parameters of the semiconductors used in the simulation can be found in Ref. [19].

3. Results and discussion

Figure 1(a) shows the simulated light–current (*L*–*I*) performance curve of the LEDs with P-AlGaN and AlGaN/GaN SLs. It can be seen that the difference between the two structures is very small at low injection current. With the injection current increasing further, the difference between the two LEDs is enlarged. The output power of the LED with AlGaN/GaN SLs increases linearly as the forward current increases, but for the LED with P-AlGaN, the output power increases slowly. The light output power of the LED with AlGaN/GaN SLs is about twice as large as that of the LED with P-AlGaN at 300 mA. The IQEs of the LEDs with P-AlGaN and AlGaN/GaN SLs, each as a function of injection current, are shown in Fig. 1(b). As the forward current increases, the two LED structures show different characteristics. The efficiency droop of the LED with AlGaN/GaN SLs at 300 mA is improved remarkably as compared with that with P-AlGaN.

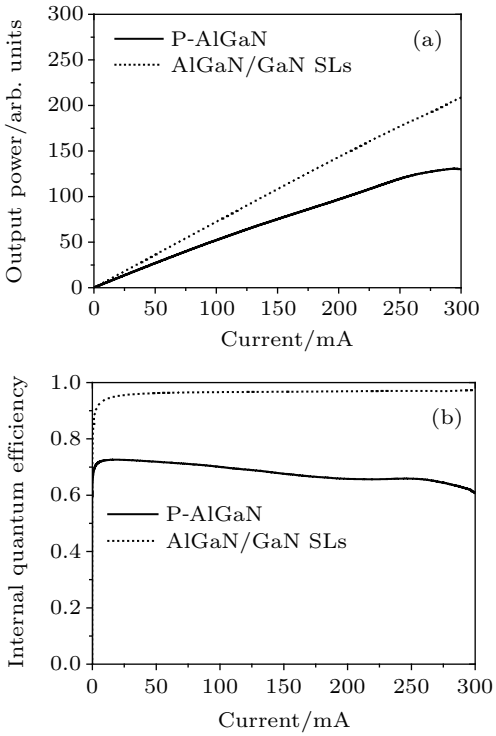


Fig. 1. (a) *L*–*I* curves of the LEDs with P-AlGaN and AlGaN/GaN SLs, and (b) the IQE of the LEDs with P-AlGaN and AlGaN/GaN SLs.

Figure 2 shows the band diagrams and quasi-Fermi levels of the LEDs with P-AlGaN and AlGaN/GaN SLs at 300 mA. It is indicated in Fig. 2(a) that for the LED with P-AlGaN, the strong electric field caused by the piezoelectric polarization charges at the interface between the P-AlGaN and barrier layer lowers the conduction band energy in the last barrier. This has a negative effect on the confinement of electrons at high carrier density. However, in Fig. 2(b), AlGaN/GaN SLs have been employed for strain relief and consequently have a smaller internal

piezoelectric field, which is caused by lower lattice mismatch in the active region and, hence, the band bending situation can be improved. Therefore, the overlap of electron and hole wave functions and the probability of radiative recombination can be markedly enhanced. In Fig. 2, curves 1 and 3 are the effective potential barriers for electrons, and curves 2 and 4 are the effective potential barriers for holes that are caused by the band bending effect. Curve 3 is much higher than curve 1, and the enhancement of the potential height of the layer is beneficial for reducing the electron leakage current. In the meantime, the effective potential barrier 4 is much lower than 2 for the holes. Thus, it is easier for holes to be injected into the active layer of the LED with AlGaN/GaN SLs than with P-AlGaN. The LED with AlGaN/GaN SLs, when electrons are prevented from overflowing into the fifth QW, enables more efficient hole transport across the EBL than the LED with P-AlGaN.

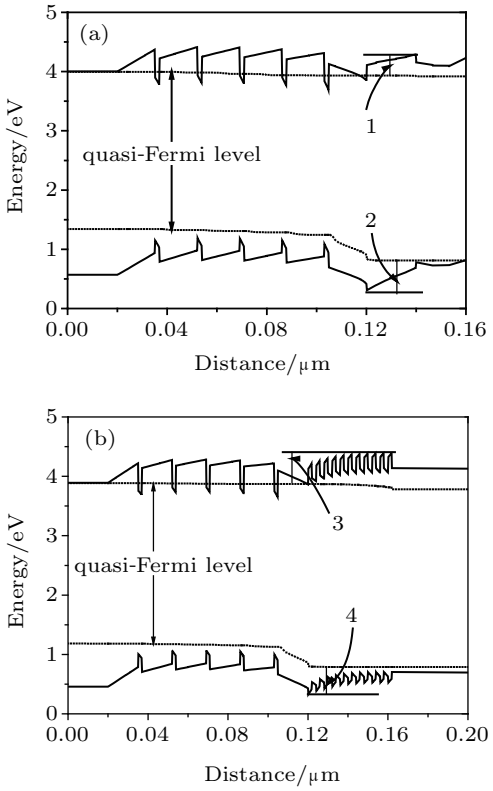


Fig. 2. Band diagrams and quasi-Fermi levels of the LEDs with (a) P-AlGa, and (b) AlGaN/GaN SLs at 300 mA.

Figure 3 shows the hole and electron concentrations of the LEDs with P-AlGaN and AlGaN/GaN SLs in an MQW region at 300 mA. It is found that the electron concentration and the hole concentration of the LED with AlGaN/GaN SLs increase drastically in the QW compared with those of the LED with P-AlGaN. Figure 3(a) indicates that when the LED is with P-AlGaN, most holes are transported with difficulty in the active region and thus accumulate in the QW close to the p-side layer, owing to their large effective mass and low mobility. However, when the LED is with AlGaN/GaN SLs, more holes can be transported easily to the QW close to the n-side layer and a more uniform hole injection is achieved, which implies that the AlGaN/GaN SLs can enhance hole concentration and improve the efficiency of hole carrier transport. Moreover, as shown in Fig. 3(b), for the LED with P-AlGaN, most electrons are transported in the active region easily, and thus accumulate at the QW near the p-side layer due to their small effective mass and high mobility. However, when the AlGaN/GaN SL is used as the EBL, the concentration of electrons in the last QW, which is close to the p-side layer, is relatively reduced.

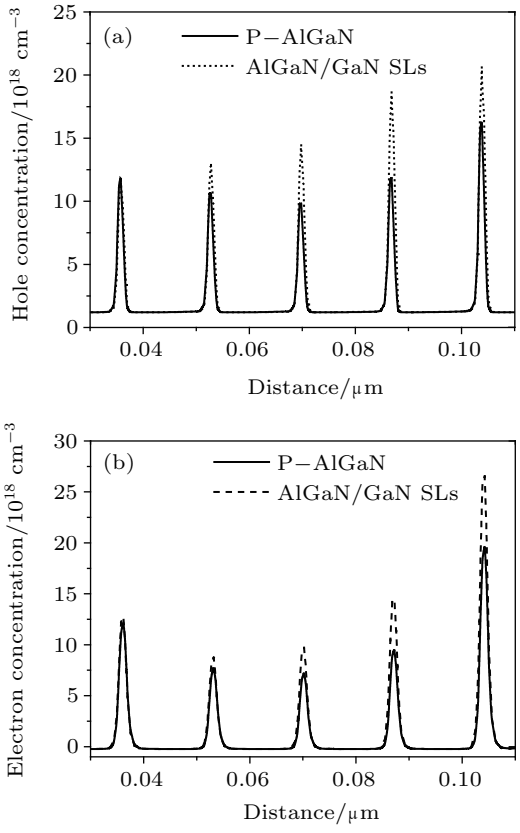


Fig. 3. (a) Hole and (b) electron concentrations of the LEDs with P-AlGaN and AlGaN/GaN SLs at 300 mA.

The corresponding radiative recombination rates of the LEDs with P-AlGaN and AlGaN/GaN SLs at 300 mA are shown in Fig. 4, respectively. For the LED with P-AlGaN, the radiative recombination rate is dominated by the QW close to the p-side layer as a result of nonuniform distributions of electrons and holes. While in the LED with AlGaN/GaN SLs, due to the enhancement of carrier concentrations and the

improvement of the efficiency of hole carrier transport, the radiative recombination rate is more uniform in QWs and almost all QWs can contribute to output power. Thus, IQE droop at high current may be improved due to the uniform distributions of electrons and holes in the QWs.

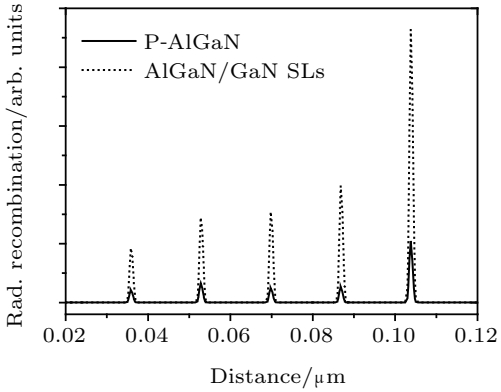


Fig. 4. Radiative recombination rates of the LEDs with P-AlGaN and AlGaN/GaN SLs at 300 mA.

4. Conclusions

The optical characteristics of blue InGaN multiple quantum-well light-emitting diodes with P-AlGaN and AlGaN/GaN SL EBLs are studied in this article by using the APSYS simulation program. The simulation results show that for LEDs with P-AlGaN and AlGaN/GaN SLs, the use of AlGaN/GaN SLs as the EBL may be beneficial for blocking the electrons from overflowing into the p-layers, while AlGaN/GaN SLs also enhance hole concentration in the active region and improve the efficiency of hole carrier transport. Therefore, the radiative efficiency and the output power can be markedly improved at high current. The LED with AlGaN/GaN SLs has a better optical performance.

References

[1] Koike M, Shibata N, Kato H and Takahashi Y 2002 *IEEE J. Sel. Topics Quantum Electron.* **8** 271

[2] Sebitosi A B and Pillay P 2007 *IEEE Trans. Energy Convers.* **22** 674

[3] Ni X, Fan Q, Shimada R, Ozgur U and Morkoc H 2008 *Appl. Phys. Lett.* **93** 171113

[4] Xie J, Ni X, Fan Q, Shimada R, Özgür Ü and Morkoç H 2008 *Appl. Phys. Lett.* **93** 121107

[5] Rozhansky V and Zakheim D A 2007 *Phys. Status Solidi* A **204** 227

[6] Cabalu J S, Thomidis C, Moustakas T D, Riyopoulos S, Zhou L and Smith D J 2006 *J. Appl. Phys.* **99** 064904

[7] Kim M H, Schubert M F, Dai Q, Kim J K, Schubert E F, Piprek J and Park Y 2007 *Appl. Phys. Lett.* **91** 183507

[8] Rozhansky I V and Zakheim D A 2006 *Semiconductors* **40** 839

[9] Shen Y C, Mueller G O, Watanabe S, Gardner N F, Munkholm A and Krames M R 2007 *Appl. Phys. Lett.* **91** 141101

[10] Chen Y X, Shen G D, Guo W L, Xu C and Li J J 2011 *Chin. Phys.* B **20** 017204

[11] Lu W, Xu M, Wei Y and He L 2011 *Acta Phys. Sin.* **60** 087807 (in Chinese)

[12] Zheng Q H, Yin Y A, Zhu L H, Huang J, Li X Y and Liu B L 2009 *Appl. Phys. Lett.* **94** 222104

[13] Liu J P, Limb J B, Ryou J H, Lee W, Yoo D, Horne C A and Dupuis R D 2008 *J. Electron. Mater.* **37** 558

[14] Jang J S 2008 *Appl. Phys. Lett.* **93** 081118

[15] Xing Y H, Deng J, Han J, Li J J and Shen G D 2009 *Acta Phys. Sin.* **58** 590 (in Chinese)

[16] Liu Y J, Yen C H, Chen L Y, Tsai T H, Tsai T Y and Liu W C 2009 *IEEE Electron Dev. Lett.* **30** 11

[17] Kim K S, Kim J H, Jung S J, Park Y J and Cho S N 2010 *Appl. Phys. Lett.* **96** 091104

[18] Stringfellow G B and Craford M G 1997 *High Brightness Light Emitting Diodes* (San Diego: CA Academic) p. 412

[19] Vurgaftman I and Meyer J R 2003 *J. Appl. Phys.* **94** 3675